Assessment of Ground-Water Storage Through Artificial Recharge at Six Sites in the Methow River Basin, Washington

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1. Introduction

Shallow ground water in surficial deposits of unconsolidated sediment is an important resource in the Methow River Basin (MRB), in north-central Washington State. Shallow ground water is used widely for domestic supplies and may be used increasingly for new residential and commercial development and for irrigation, as an alternative to surface-water diversion. Shallow ground water also sustains streamflow in rivers and streams from late summer to spring.

Streamflow during high-flow periods, in late spring and early summer, may be used to recharge shallow, unconsolidated aquifers to increase ground-water supplies and streamflow during low-flow periods later in the year. Shallow aquifers can be recharged artificially by distributing water over the land surface (such as in ponds), in the soil column (such as through perforated pipes), or directly to the aquifer (such as through injection wells). Regardless of the methods used, the effectiveness of artificial recharge depends on the availability of streamflow for artificial recharge, the storage capacity of the aquifers, and the amount of time the recharged ground water will stay in the aquifer (residence time).

The U.S. Geological Survey (USGS), in cooperation with Okanogan County, studied the potential for using artificial recharge to increase ground-water storage in the MRB at six sites selected by the Methow Basin Planning Unit (fig. 1). The Planning Unit selected sites where artificial recharge might be possible with a minimum of construction or engineering. The study involved assessing the availability of streamflow for artificial recharge in the MRB, the conditions affecting ground-water storage at the six sites, and the potential at each site for hazards associated with artificial recharge. This report presents the results of this study and provides a preliminary assessment of the feasibility of using artificial recharge at these sites to increase ground-water storage. The information can be used as a basis for more comprehensive evaluations of options for addressing specific water-resources management issues in the MRB.

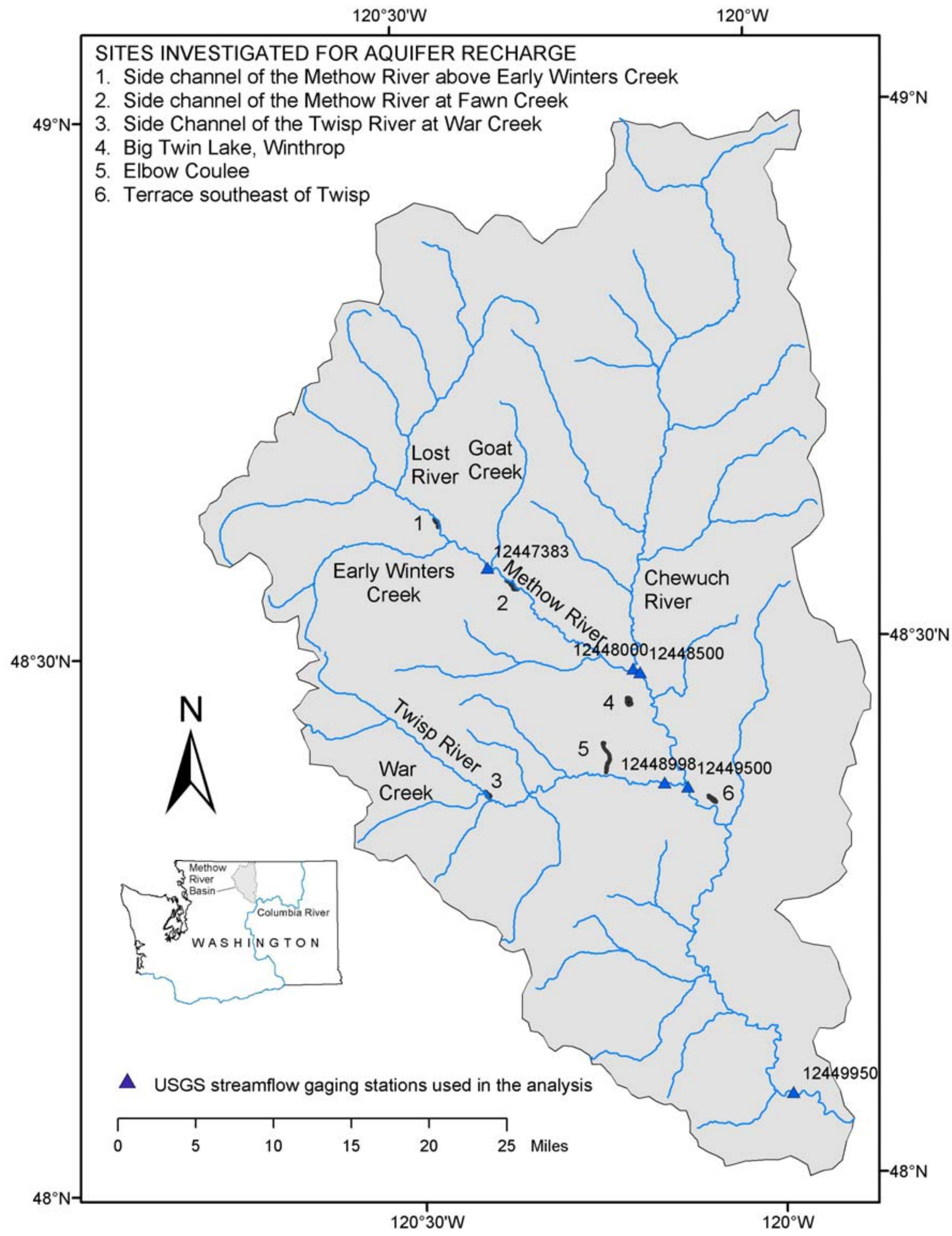


Figure 1. Location of sites assessed for potential use of artificial recharge and selected U.S. Geological Survey streamflow-gaging stations in the Methow River Basin, Washington.

2. Assessment of Availability of Streamflow for Artificial Recharge

The availability of streamflow for artificial recharge at the six sites in the MRB was assessed by comparing daily streamflow records from six USGS streamflow-gaging stations, downstream from the sites (fig. 1), to Washington State regulatory base flows. Washington State has established regulatory base flows at each of these stream stations to determine the availability of water for out-of-stream uses and for protecting in-stream uses of water (Washington Administrative Code 173-548-020(2)). Unlike hydrologic base flow, which represents the relatively stable discharge in a stream during periods without precipitation or snowmelt, regulatory base flow is a minimum discharge used for administering the appropriation of water. Regulatory base flow is only one factor that could limit the availability of water for artificial recharge. There are likely to be other factors, particularly in locations where, even if regulatory base flows are satisfied, diversion of streamflow for artificial recharge has negative ecological or social effects. This study considered only the limit of regulatory base flow in the assessment of steamflow availability.

2.1 Methods for Assessing Streamflow Availability

Daily discharge records for water years 1993-2002 and regulatory base flows were compared at six streamflow-gaging stations to determine the volume and period when streamflow would have been available for artificial recharge at each station. (A water year begins on October 1 of the previous calendar year.)

Methow River above Goat Creek (station 12447383)
Chewuch River at Winthrop (station 12448000)
Methow River at Winthrop (station 12448500)
Twisp River near Twisp (station 12448998)
Methow River at Twisp (station 12449500)
Methow River near Pateros (station 12449950)

Regulatory base flows are listed for the 1st and 15th days of each month at each station (table 1), and regulatory base flows for all other days were estimated by linear interpolation between those values.

Table 1. Washington State regulatory base flows at six U.S. Geological Survey streamflow-gaging stations in the Methow River Basin, Washington

	Regulatory base flow (cubic feet per second)					
Day	Methow River above Goat Creek (USGS station 12447383)	Chewuch River at Winthrop (USGS station 12448000)	Methow River at Winthrop (USGS station 12448500)	Twisp River near Twisp (USGS station 12448998)	Methow River at Twisp (USGS station 12449500)	Methow River near Pateros (USGS station 12449950)
Oct 1	45	56	122	35	260	360
Oct 15	60	68	150	45	320	425
Nov 1	60	68	150	45	320	425
Nov 15	60	68	150	45	320	425
Dec 1	51	62	135	39	290	390
Dec 15	42	56	120	34	260	350
Jan 1	42	56	120	34	260	350
Jan 15	42	56	120	34	260	350
Feb 1	42	56	120	34	260	350
Feb 15	42	56	120	34	260	350
Mar 1	42	56	120	34	260	350
Mar 15	42	56	120	34	260	350
Apr 1	64	90	199	60	430	590
Apr 15	90	140	300	100	650	860
May 1	130	215	480	170	1000	1300
May 15	430	290	690	300	1500	1940
Jun 1	1160	320	790	440	1500	2220
Jun 15	1160	320	790	440	1500	2220
Jul 1	500	292	694	390	1500	2150
Jul 15	180	110	240	130	500	800
Aug 1	75	70	153	58	325	480
Aug 15	32	47	100	27	220	300
Sep 1	32	47	100	27	220	300
Sep 15	32	47	100	27	220	300

The period of water years 1993-2002 is generally representative of the long-term average streamflow conditions in the basin, as well as its inter-annual variation, as can be seen by comparing streamflow statistics for 1993-2002 for the Methow River near Pateros with statistics for water years 1960-2002, the period of record for that station (table 2). Mean discharge for the Methow River near Pateros was 1,562, ft^3/s (cubic feet per second) for 1993-2002 and 1,550 ft^3/s for the period of record. The median annual discharge was 1,647 ft^3/s for water years 1993-2002 and 1,567 ft^3/s for the period of record. Annual variation in streamflow during the two periods was similar, with a coefficient of variation for annual discharge of 1.5 for each period.

Table 2. Comparison of annual streamflow statistics for the period of record (water years 1960-2002) and the period of artificial-recharge analysis (water years 1993-2002) for the Methow River Basin near Pateros, Washington; cfs, cubic feet per second.

Streamflow statistics	Period of record, water years 1960-2002	Period of analysis, water years 1993-2002
Mean discharge	1550 cfs	1562 cfs
Median annual discharge	1567 cfs	1647 cfs
Minimum annual discharge	565 cfs	576 cfs
Maximum annual discharge	3413 cfs	2251 cfs
Coefficient of variation of daily mean discharge	1.5	1.5

2.2 Streamflow Availability

The mean streamflow in excess of regulatory base flows for each station was calculated as the sum of the differences between daily streamflow and regulatory base flow for each day of the year. There was a net excess of streamflow above regulatory base flow on average for water years 1993-2002 at all six gages in the Methow River Basin (table 3). Excess streamflow for the period ranged from 153 ft^3/s for the Twisp River near Twisp to 917 ft^3/s for the Methow River at Winthrop. There was an annual net excess of streamflow volume in all years except water year 2001, when the total volume of streamflow was less than the total regulatory base flow at all of the stations except the Methow River at Winthrop (table 4).

Table 3. Mean streamflow in excess of Washington State regulatory base flow for water years 1993-2002 at six streamflow-gaging stations in the Methow River Basin, Washington

Streamflow-gaging station	Mean streamflow in excess of regulatory base flow (cubic feet per second)
Methow River above Goat Creek	336
Chewuch River at Winthrop	296
Methow River at Winthrop	944
Twisp River near Twisp	162
Methow River at Twisp	887
Methow River near Pateros	815

Table 4. Annual net streamflow in excess of Washington regulatory base flows for water years 1993-2002 at six streamflow-gaging stations in the Methow River Basin, Washington. Negative values indicate that annual streamflow was less than regulatory flow.

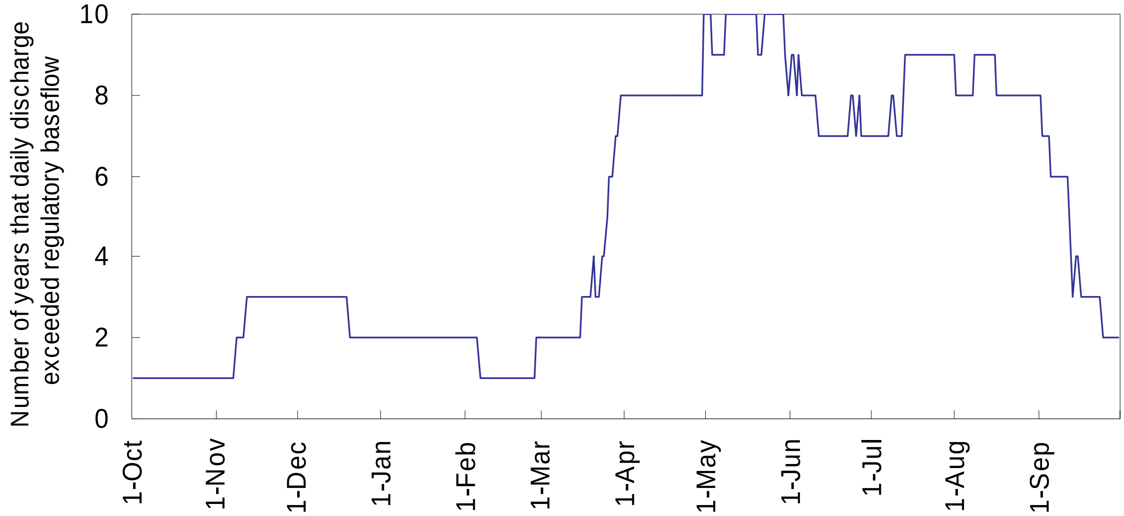
Water year	Methow River above Goat Creek	Chewuch River at Winthrop	Methow River at Winthrop	Twisp River near Twisp	Methow River at Twisp	Methow River near Pateros
			(cubic feet per second)			
1993	123	163	557	61	410	275
1994	100	169	500	43	364	215
1995	405	415	1186	232	1215	1106
1996	505	417	1313	301	1378	1307
1997	539	468	1382	276	1385	1380
1998	404	398	1166	186	1133	1166
1999	612	517	1471	235	1431	1503
2000	314	221	810	139	768	693
2001	-33	-11	172	-9	-30	-171
2002	395	203	885	155	814	673

Daily streamflow exceeded regulatory base flow on most days in most years (table 5). The median number of days each year when streamflow exceeded regulatory base flows was 189 days for the Methow River above Goat Creek and 220 days for the Methow River near Pateros, the sites with the fewest number of days when streamflow exceeded regulatory base flows. In drier years (such as 1993, 1994, and 2001), however, daily streamflow frequently did not meet regulatory base flow at many stations in the MRB.

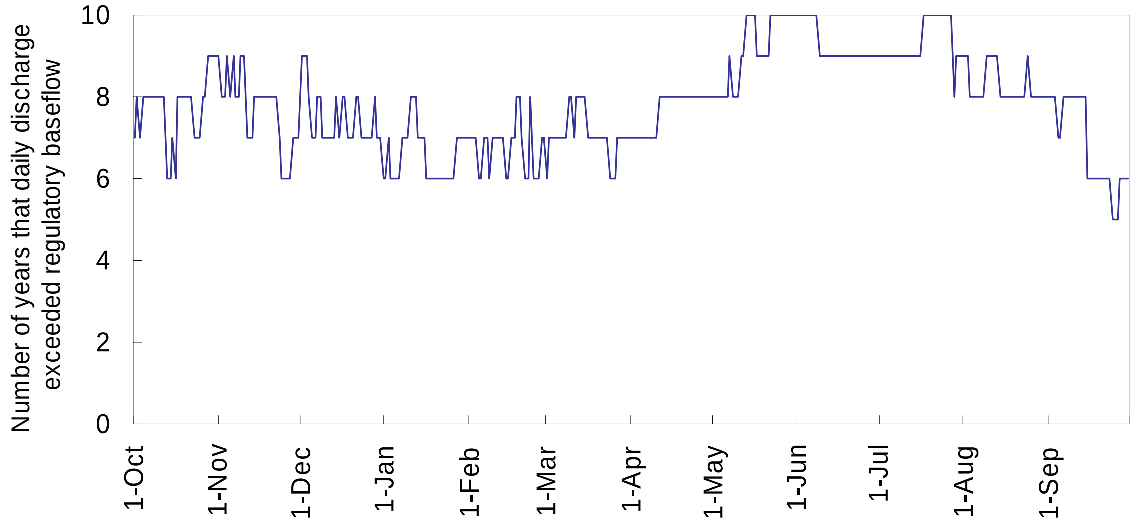
Table 5. Number of days when streamflow exceeded regulatory base flow for water years 1993-2002 at six streamflow-gaging stations in the Methow River Basin, Washington.

Water year	Methow River above Goat Creek	Chewuch River at Winthrop	Methow River at Winthrop	Twisp River near Twisp	Methow River at Twisp	Methow River near Pateros
			(days)			
1993	106	196	337	211	130	116
1994	94	286	365	158	157	89
1995	198	285	365	335	234	220
1996	321	365	366	366	366	358
1997	193	365	365	365	361	333
1998	250	365	365	354	354	364
1999	189	365	365	365	310	325
2000	247	350	366	354	351	353
2001	26	85	326	152	66	15
2002	171	193	365	315	206	185
Median	191	318	365	345	272	273

The seasonal pattern of streamflow availability at each station can be assessed by examining the number of years during water years 1993-2002 that streamflow for each day of the year exceeded regulatory base flow (fig. 2). At most stations, daily streamflow exceeded regulatory base flow from March through July. Streamflow was less than regulatory base flow during September in most years at all stations except the Chewuch River at Winthrop (fig. 2b) and the Methow River at Winthrop (fig. 2c). Likewise, daily streamflow was less than regulatory base flow in most years from September through March at the Methow River above Goat Creek (fig. 2a), the Methow River at Twisp (fig. 2e), and the Methow River near Pateros (fig. 2f).

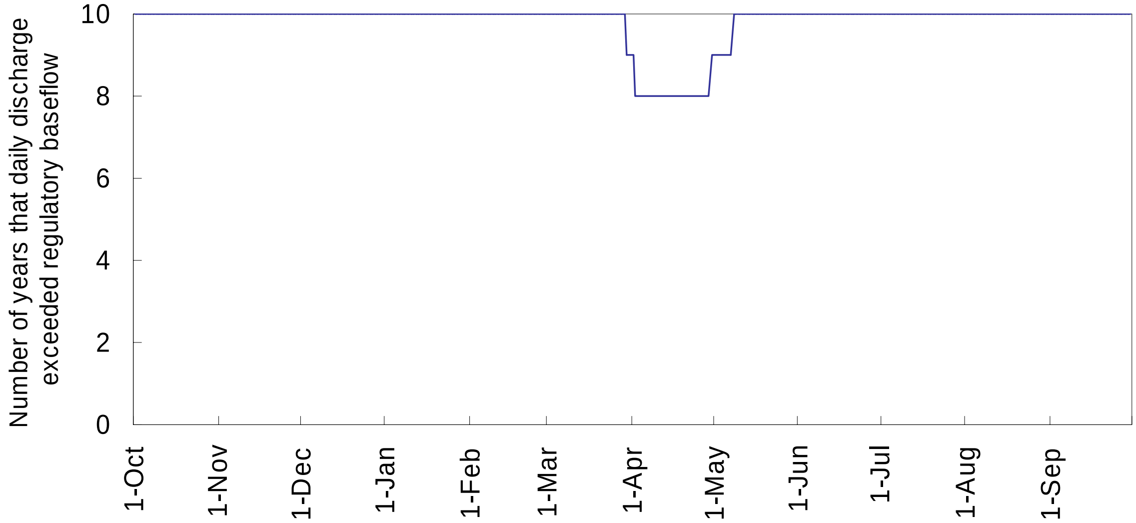


a. Methow River above Goat Creek (USGS station 12447383)

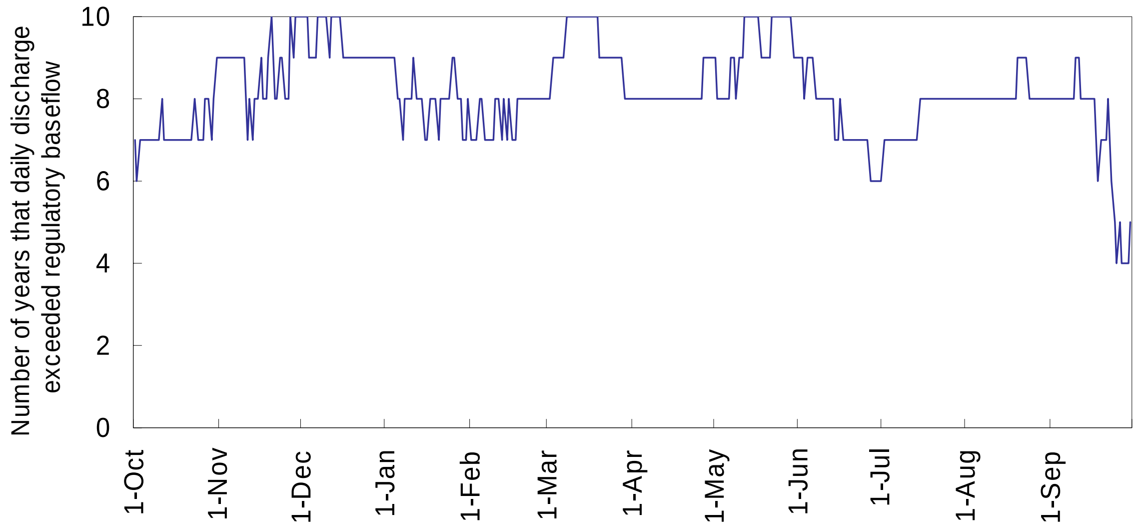


b. Chewuch River at Winthop (USGS station 12448000)

Figure 2. Number of years during water years 1993-2002 that streamflow for each day of the year exceeded regulatory base flows at six sites in the Methow River Basin, Washington.

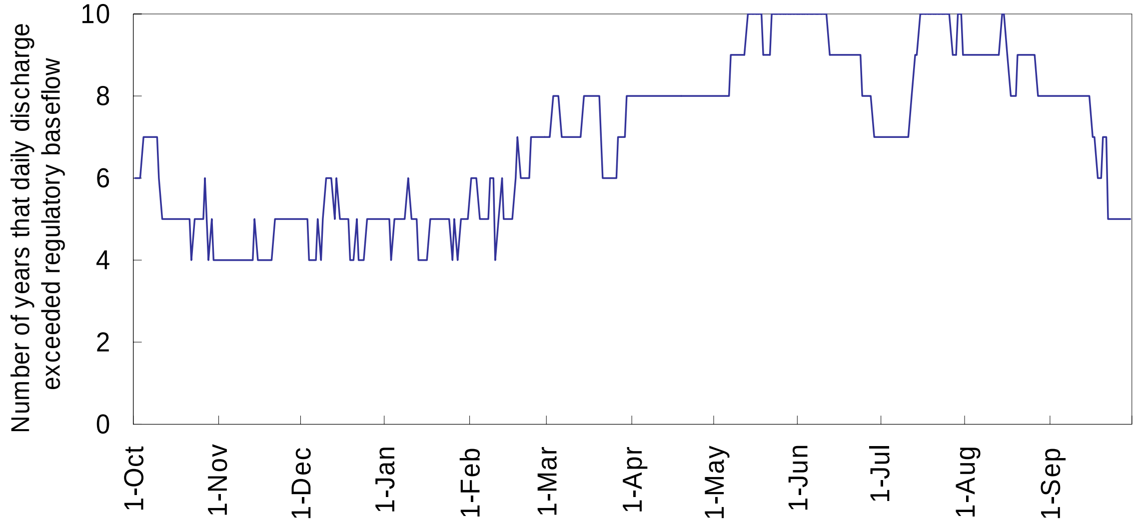


c. Methow River at Winthrop (USGS station 12448500)

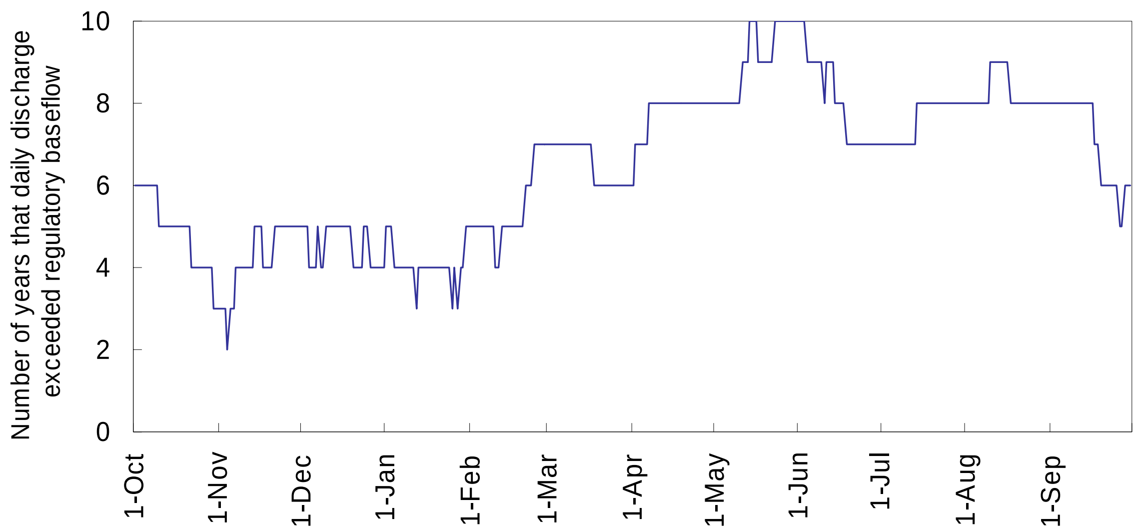


d. Twisp River near Twisp (USGS station 12448998)

Figure 2 continued.



e. Methow River at Twisp (USGS station 12449500)



f. Methow River near Pateros (USGS station 12449950)

Figure 2 continued.

There were days in every year when streamflow exceeded regulatory base flow. The annual volume of streamflow on days when streamflow exceeded regulatory base flow ranged from 9,000 acre-ft for the Chewuch River at Winthrop in water year 2001 to 1,090,000 acre-ft for the Methow River near Pateros in water year 1999 (table 6). Although streamflow exceeded regulatory base flow on some days during the 2001 drought at all stations, the annual volume of daily streamflow of the Methow River near Pateros that exceeded State regulatory base flow was only 32,000 acre-ft (table 6).

Table 6. Annual volume of streamflow in excess of regulatory base flow for days when streamflow exceeded regulatory base flow at six sites in the Methow River Basin, Washington.

Water year	Methow River above Goat Creek	Chewuch River at Winthrop	Methow River at Winthrop	Twisp River near Twisp	Methow River at Twisp	Methow River near Pateros
	thousands of acre feet					
1993	122	127	408	53	347	301
1994	105	124	362	41	279	215
1995	308	301	859	169	894	826
1996	370	303	953	218	1001	949
1997	403	339	1000	200	1003	1001
1998	297	288	844	135	821	844
1999	460	374	1065	170	1039	1090
2000	232	160	588	101	558	503
2001	25	9	133	12	55	32
2002	301	150	641	113	603	511

The availability of streamflow for artificial recharge at a site is likely to be limited at some times by regulatory base flow at a station immediately downstream, but also by regulatory base flow for the Methow River near Pateros (fig. 2f). Thus, artificial recharge may be feasible at any site in the MRB only during the spring and summer in years when streamflow is close to average or higher.

3. Hydrogeologic Characteristics Affecting Artificial Recharge at Six Sites

The Methow Basin Planning Unit identified six sites to assess for artificial recharge (fig. 1). The sites represent two types of landscape feature: floodplains, and terraces or valley-fill deposits above floodplains (table 7). The feasibility of artificial recharge at a site will depend in part on the site type. Floodplains are located along rivers, so streamflow may be easily supplied to a floodplain for artificial recharge. Artificial recharge at these sites may be possible with a minimum of construction by flooding existing side channels and allowing the streamflow to infiltrate into the ground. Such projects may provide ancillary ecological benefits by increasing aquatic habitat during recharge periods. In contrast, at terraces and valley-fill deposits water must be conveyed longer distances than at floodplains and structures (ponds, infiltration galleries, wells) would have to be constructed at the sites.

Table 7. Landscape features and soil types at six sites assessed for potential artificial recharge in the Methow River Basin, Washington.

	Site	Landscape feature	Soils
1	Methow River above Early Winters Creek	Floodplain	Not available[1]
2	Methow River at Fawn Creek	Floodplain	Xerofluvents, Boesel fine sandy loam, and riverwash[2]
3	Twisp River at War Creek	Floodplain	Not available[1]
4	Big Twin Lake, Winthrop	Glacial terrace	Owhi extremely stony fine sandy loam[2]
5	Elbow Coulee	Glacio-fluvial valley-fill deposit	Newbon gravelly loam[2]
6	Terrace southeast of Twisp	Glacio-lacustrine terrace	Newbon gravelly loam, Winthrop gravelly loamy sand, Newbon loam[2]

[1]Not included in the Okanogan County Soil Survey, but likely to have riverwash and Boesel fine sandy loam.
[2]Source: Okanogan County Soil Survey (Soil Conservation Service, 1980).

Each type of site has distinct characteristics that affect its suitability for artificial recharge. Recharge and storage in floodplain areas are likely to be limited by a high ground-water table, lenses of fine-grained sediment with low permeability, and short ground-water flow paths back to the river that reduce residence time. Aquifer recharge and storage in terraces and valley-fill deposits may be limited by the same conditions, but ground-water tables are likely to be deeper and flow paths back to rivers longer.

Artificial recharge will increase ground-water storage only when three conditions are satisfied: (1) the streamflow used to recharge the aquifer would not naturally recharge the aquifer; (2) storage space is available in the aquifer during periods of excess streamflow; and (3) the residence time and movement of the artificially recharged ground water is consistent with its intended use. Condition 1 was addressed by assessing the availability of streamflow at gages downstream from each recharge site to account for losses of streamflow that represent natural (fluvial) recharge of the unconsolidated aquifer by a river. The diversion of surface water for artificial recharge may lower the stage (water surface) in a river and, as consequence, reduce fluvial recharge. The effect of lower stage on fluvial recharge also depends on the magnitude of the change in stage relative to the depth of water in the channel, but this was not assessed in this study.

Condition 2 was addressed by analyzing the depth to the water table at each site during the summer of 2001 when ground-water levels generally were at their annual maximum. The depth to the water table represents the maximum thickness of the unsaturated sediments that could be used to store water under atmospheric pressure. The aquifer formed by unconsolidated sediments may be confined in places, but the confining units are not continuous (Konrad and others, 2003); therefore, artificial recharge is assumed to take place under atmospheric pressure (unconfined conditions).

Condition 3 depends on hydraulic conditions at an artificial-recharge site and on the time and location of intended uses for artificially recharged ground water. Because there were no specific artificial-recharge projects at the time of the study, the time and location of intended uses of artificially recharged ground water were not considered. There are, however, two likely situations for using artificial recharge in the MRB: increased ground-water supplies for domestic, agricultural, and other commercial uses and increased ground-water discharge to rivers to increase streamflow (instream use).

Hydraulic conditions affecting the residence time and movement of artificially recharged ground water include the hydraulic conductivity of the aquifer, the hydraulic gradient between a recharge site and the river, and the distance separating the site and the river. The unconsolidated sediments forming the shallow aquifer in the Methow River Basin generally have high hydraulic conductivities (greater than 100 ft per day; Konrad and others, 2003), however layers of fine-grained sediments, which are likely to be much less conductive, are also common. These layers could impede vertical flow and thus reduce recharge rates. The artificially recharged ground water also could remain above these layers, which effectively reduces the storage capacity of the unsaturated zone. Fine-grained layers close to the land surface also could promote shallow horizontal ground-water flow, which limits the residence of recharged water, particularly at sites close to rivers. A water table close to the land surface will also allow only a short residence time for artificially recharged water because of short horizontal ground-water flow paths from a recharge site back to a river.

The hydraulic gradient of the regional ground-water system and the horizontal length of ground-water flow paths to the nearest river channel that were determined for each site in this study may not be adequate for estimating the residence time and movement of artificially recharged ground water, because artificial recharge is likely to cause an increase in ground-water levels (mounding) underneath a recharge site. Mounding of ground water will increase the horizontal hydraulic gradient and horizontal flow of ground water from a recharge site and, as a consequence, may reduce the residence time and volume of ground water stored by artificial recharge. For example, ground-water mounding of 1 to 5 ft was observed in the lower Twisp River valley in two wells located between 100 and 1,000 ft from an irrigation canal, but had dissipated approximately 2 months after the flow in the canal was shut off for the season (Konrad and others, 2003). During the period when the water table was elevated, ground-water discharge to the river was also greater.

3.1 Methods for Assessing Hydrogeologic Conditions Affecting Artificial Recharge

Depth to the water table, potential storage capacity of the unsaturated sediment, distance along the subsurface flow path to the nearest river channel, and the hydraulic gradient were determined for each of the six sites. Ground-water levels at each site were interpolated from measurements of water levels at 254 wells in unconsolidated sediments in the Methow River Basin (Konrad and others, 2003) and land-surface altitudes for 29 points along rivers taken from the National Elevation Dataset (NED) (U.S. Geological Survey, 2003) using a geographic information system (GIS). These data represent seasonally high ground-water levels in the basin.

The depth to the water table was calculated as the difference between the altitude of the land surface (U.S. Geological Survey, 2003) and the water-table altitude for a 30-meter grid in each site. The potential storage capacity of the unsaturated sediment above the water table was calculated as the product of the mean depth to the water table, the site area, and an assumed porosity of 25 percent for the sediment for all of the sites except Big Twin Lake. For Big Twin Lake, the storage capacity was expressed as the volumetric equivalent to a 1-foot increase in the water level of the lake, not accounting for any increased inundation area beyond the current lake area (table 8).

Table 8. Area and selected hydraulic characteristics of the six sites assessed for artificial recharge in the Methow River Basin, Washington.

Site	Area (acres)	Infiltration rate[1] (inches per day)	Maximum recharge rate for site (acre ft per day)	Storage capacity of unsaturated sediment above water table (acre ft)
Methow River above Early Winters Creek	45	3	267	82
Methow River at Fawn Creek	62	3	370	36
Twisp River at War Creek	50	3	299	57
Big Twin Lake, Winthrop	78	4	621	78[2]
Elbow Coulee	86	1.3	222	2778
Terrace southeast of Twisp	55	5	546	1066

[1]Source: Okanogan County Soil Survey (Soil Conservation Service, 1980).

[2]Storage volume per foot increase in water level of lake.

Horizontal flow paths were determined by manually digitizing lines from the boundary of the each site, perpendicular to equipotential (contour) lines of the ground water, to the point of intersection with a river. The actual flow paths have a vertical component and are likely to deviate from the paths depicted because of variation in the hydraulic conductivity within the unconsolidated sediment. As a result, actual flow paths are likely to be longer than the estimates presented here. The hydraulic gradient was calculated on the basis of the distance of a flow path and the difference between ground-water altitude at the beginning point of the flow path (at a recharge site) and the land-surface altitude at the river where the flow path terminated.

Sites 1-3 were surveyed in April 2003 to locate the primary side channels, water surfaces, and altitudes of the side channels relative to the adjacent river channels. Surveys were conducted with a TOPCON total station and HP48GX/TDS surveying system with an angular accuracy of 5 seconds and an accuracy of about 4 mm for the electronic distance meter.[1] Surveys at sites 1 and 2 included nearby benchmarks to georeference the surveyed points. A handheld global positioning system (GPS) receiver was used to obtain the approximate geographic coordinates of the surveyed points in site 3. The length, width, and area of the primary side-channels were calculated from the surveys of the floodplain sites (table 9).

Table 9. Dimensions of side channels at sites 1-3 in the Methow River Basin, Washington.

Site	Maximum length (ft)	Median width of channels at bank (ft) with number of cross-sections in [ ]	Area covered by side channels (acres)
Methow River above Early Winters Creek	3900	83 [3]	7.5
Methow River at Fawn Creek	5600	65 [6]	8.3
Twisp River at War Creek	3300	144 [3]	10.9

Wells in and around each site had been located in the field as part of an earlier well inventory in the Methow River Basin (Konrad and others, 2003). The local lithology and any fine-grained sediments that could represent low-permeability layers were identified in the well reports for the wells (Washington Department of Ecology, 2003) (table 10). Soil information for sites 2, 4, 5, and 6 was compiled from the Soil Conservation Service (1980). Soils at the other sites were not mapped by Soil Conservation Service.

[1] Any use of trade, product, or firm names in this publication is for descriptive purposes only and does not imply endorsement by the U.S. Government

Table 10. Principal lithology and altitudes of tops of potential low-permeability layers at wells near six sites in the Methow River Basin, Washington.

Local well numbers[1]	Land surface Altitude (ft above NAVD 88)	Principal lithology	Top altitude of potential low-permeability layers (ft)
Methow River above Early Winters Creek			
36N/19E 22C [E-12]	2205	Boulders, sand, gravel	Unconsolidated sediments not differentiated
36N/19E-15L02	2214	Gravel, clay, hardpan, sand	2200 (clay), 2191 (hardpan), 2168 (hardpan)
36N/19E-15K [MW-1B]	2208	Sandy cobbles, gravel	2163 (silt)
36N/19E-22J01	2179	Gravel, boulders, silt, sand	2160 (silt)
36N/19E-22J02	2179	Silt, gravel, hardpan, sand	2158 (hardpan)
36N/19E-23E02 [EW19]	2197	Boulders, sand, gravel	None
36N/19E-23E03 [EW19A]	2197	Sand, gravel, boulders	None
Methow River at Fawn Creek			
36N/20E-04N [E-10]	1999	Not differentiated	Unconsolidated sediments not differentiated
35N/20E-04N01	2010	Cobbles, sand, gravel, silt	1978 (silt and gravel)
35N/20E-10E01	1974	Clay, sand, and gravel	1969 (clay)
Twisp River at War Creek			
33N/20E-07N01	2408	Sand, gravel, and boulders	2306 (river sand and blue clay), 2291 (clay and sandstone)

Table 10 continued.

Local well numbers[1]	Land surface altitude (ft above NAVD 88)	Principal lithology	Top altitude of potential low-permeability layers (ft)
Big Twin Lake, Winthrop			
34N/21E-15B01	1894	Sand, gravel, clay	1825 (clay)
34N/21E-15R01	1886	Till, sand, gravel	1886 (till)
34N/21E-15E01	1954	Clay, gravel, hardpan, bedrock	1938 (clay)
34N/21E-14D01	1844	Sand, gravel, bedrock	None
34N/21E-14E01	1853	Silt, sand, cobbles, gravel	1838 (cemented silt), 1818 (clay like)
34N/21E-14N01	1864	Clay, sand, gravel, silt, bedrock	1864 (clay), 1822 (silt)
34N/21E-14P01	1864	Sandy clay, gravel, bedrock	1821 (bedrock)
Elbow Coulee			
33N/21E-09D01	1974	Sand, gravel, clay	1962 (clay)
33N/21E-09D02	2004	Gravel, silt, cobbles, boulders, clay, bedrock	1974 (clay)
33N/21E-09D03	1969	Gravel, hardpan, clay	1969 (clay and gravel)
Terrace southeast of Twisp			
33N/21E-16P01	1584	Silty sand, cobbles, gravel	1554 (sand, silty; tight clay-like)
33N/21E-16R03	1673	No well log	No well log
33N/21E-16R [6”]	1673	Sand, gravel, cobbles, boulders, clay	1632 (fine to medium sand, abundant clay)
33N/21E-16R [8”]	1657	Gravel, cobbles, boulders, sand, bedrock	None

[1]Local well numbers are the Township, Range, Section, and a letter identifying the quarter-quarter section of the well described in the text. If the well has been inventoried by USGS, then a 2-digit sequence number follows the quarter-quarter section identifier. Other agency codes or descriptions for wells are listed in [ ].

3.2. Site 1, Methow River above Early Winters Creek

The floodplain southwest of the Methow River has a braided side-channel network approximately 1.5 mi upstream of Early Winters Creek (fig. 3). The network extends over approximately 45 acres (table 8), with as many as four distinct, parallel channels in places. Water flows into the network and multiple places during high flows. The main side channel is 3,900 ft long (table 9). The median combined width of the side channels at their banks is 83 ft for three cross sections.

The unconsolidated sediments are 4,000 ft wide at the land surface and 860 ft thick on the southern side of site (for example, well 36N/20E-04N [E-10]). The sediments are coarse (cobbles, sand, and gravel; table 10). Three logs were available for wells near to the site. The log of one well in the site (35N/20E-04N01) reported the top of a “silt and gravel” layer at an altitude of 1,978 ft. The log for a well close to the site (35N/20E-10E01) reported the top of a “clay” layer at an altitude of 1,969 ft. Soils at the site include xerofluvent, Boesel fine sandy loam, and river wash (table 7; Soil Conservation Service, 1980).

Depth to the water table ranges from more than 10 ft to less than 3 ft (fig. 6). The unsaturated sediments have a storage capacity of 82 acre-ft. Small, discontinuous areas of standing water were observed at six locations in the side-channel network in April 2003. The source of this water was not certain, but it may have been seepage of shallow ground water, which was perched on fine-grained facies deposited in the side-channel network. Ground water generally flows away from the river in the northern part of the site and toward the river at the southern end. The lengths of horizontal flow paths between the site and the river range from 1,800 ft to 1 mi (fig. 3). The hydraulic gradient of the water table along the flow paths is 0.01.

Streamflow would be available for artificial recharge at this site from April through August in most years, based on streamflow records for the Methow River above Goat Creek (fig. 2a). From September to March, however, streamflow is less than regulatory base flow at the Methow River above Goat Creek and, moreover, is generally less than the recharge capacity of the riverbed, which typically is dry between Lost River and Early Winters Creek in the autumn and winter. Thus artificial recharge would increase recharge only when there is flow in the Methow River above Goat Creek.

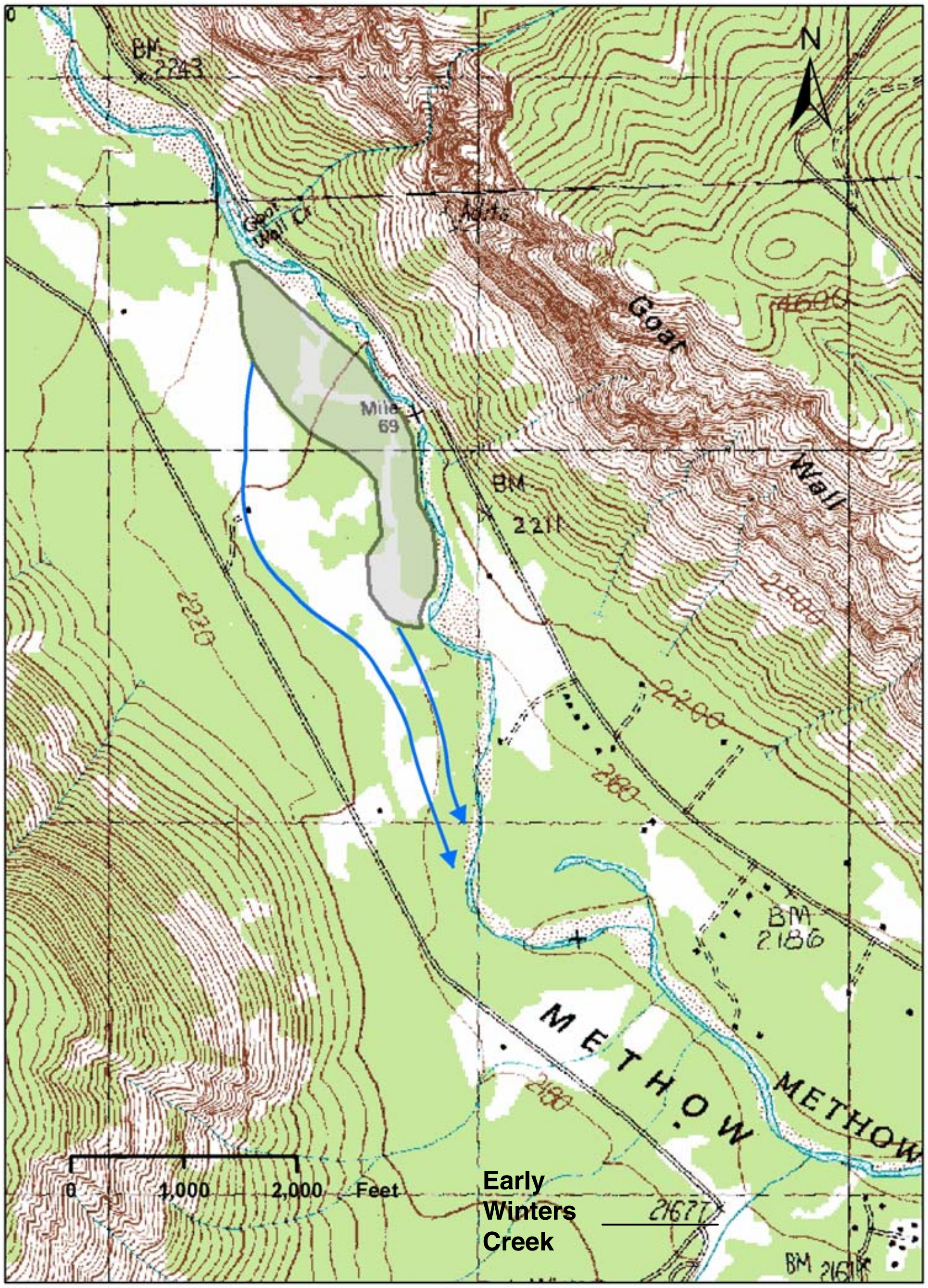


Figure 3. Location of site 1, Methow River above Early Winters Creek, in the Methow River Basin, Washington with ground-water flow paths.

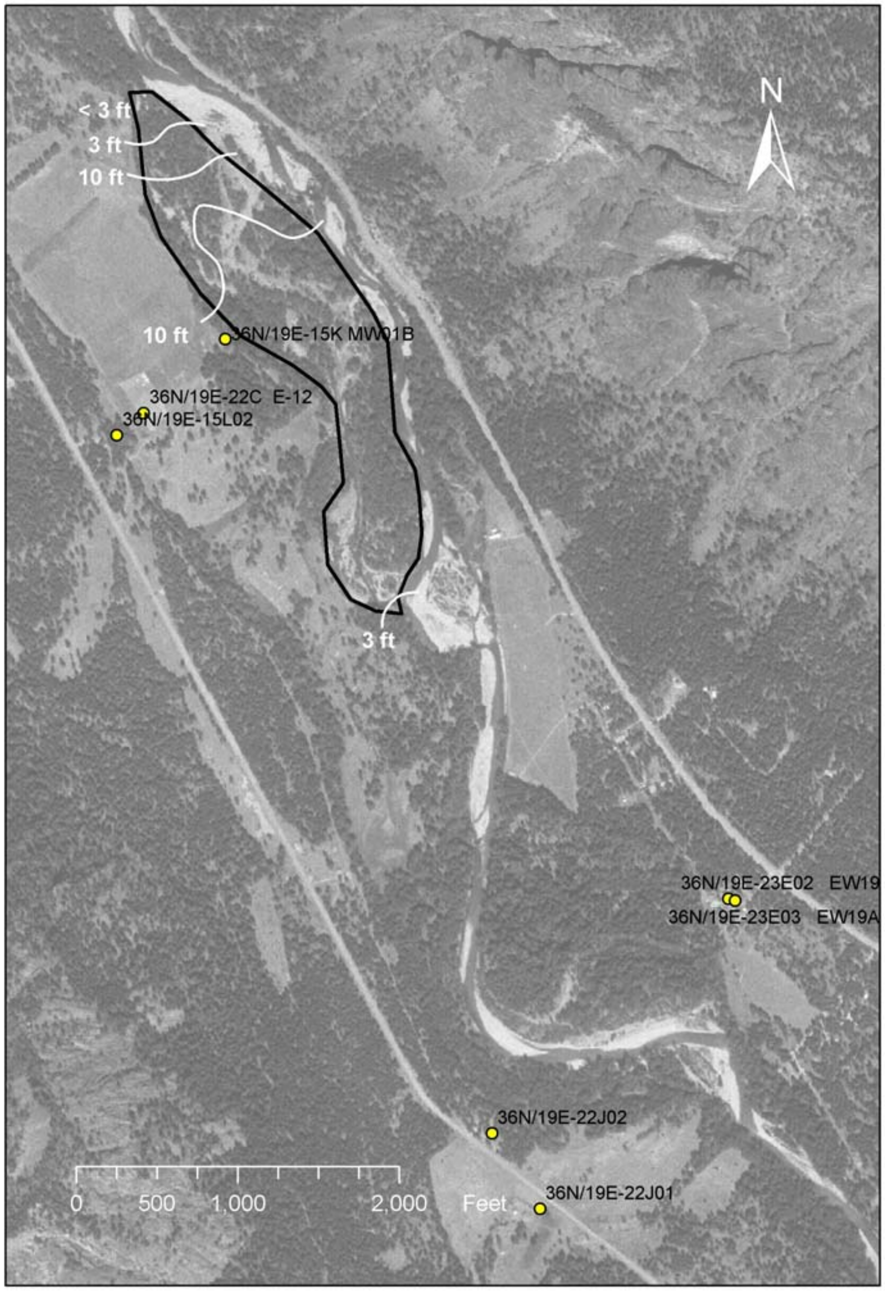


Figure 4. Ground-water wells and estimated depth to ground water at site 1, Methow River above Early Winters Creek.
Source of digital orthophotograph: U.S. Forest Service, 1998a.

3.3. Site 2, Methow River at Fawn Creek

The floodplain southwest of the Methow River has a series of side channels that begins 0.5 mi upstream of the confluence with Fawn Creek (fig. 5) and covers about 62 acres (table 8). A levee along the right river bank (facing downstream) limits inflows to the side-channels to two culverts and ground-water seepage (through the levee or from the alluvial aquifer). The main side channel is 5,600 ft long (table 9). It has been used to convey water from the Methow River to two irrigation canals. The median combined width of the side channels at their banks is 65 ft for six cross sections, however the cross section did not include all side channels.

The unconsolidated sediments in the valley are 3,400 ft wide at the land surface and more than 850 ft thick at the valley center (for example, well number 36N/19E-22C [E-12]). The sediments are mostly coarse (gravel, sand, cobbles, some clay; table 10). Although there is not a continuous layer of fine-grained material at the site, there may be shallow, discontinuous lenses of fine-grained material that could limit recharge rates and promote lateral flow in places. “Clay” was reported at one well at an altitude of 2,200 ft. Fine-grained layers, described as “silt” or “hardpan” with top altitudes ranging from 2,158 to 2,168 ft (table 10), were identified in four wells near to the site, however similar fine-grained layers were not reported in two other wells west of the site. The silt and hardpan layers are 19 to 46 ft below the land surface, which is deeper than the ground-water table in most locations.

The depth to the water table generally is less than 3 ft (fig. 6), which was confirmed by observations of ground-water seepage into the side channels and surface-flow throughout the site in April 2003. Because of the high water table, the unsaturated sediments have a storage capacity of 36 acre-ft (table 8). Ground water generally flows toward the river, with a flow path from the site to the river from less than 100 ft to 1.5 mi long (fig. 5). The hydraulic gradient between ground water at the site and the Methow River ranges along the flow paths from 0 (ground-water and surface-water levels are equal) to 0.006.

Although streamflow typically exceeds regulatory base flow for the Methow River at Winthrop (fig. 2c.), much of it is produced by ground-water discharge between Fawn Creek and Winthrop. Indeed, the Methow River above Goat Creek, which is downstream of site 1, frequently has no flow during the autumn and winter because all of the inflow to the river above

Goat Creek is lost naturally to aquifer recharge. As a result, the availability of streamflow for artificial recharge would be limited to spring and summer in many years.

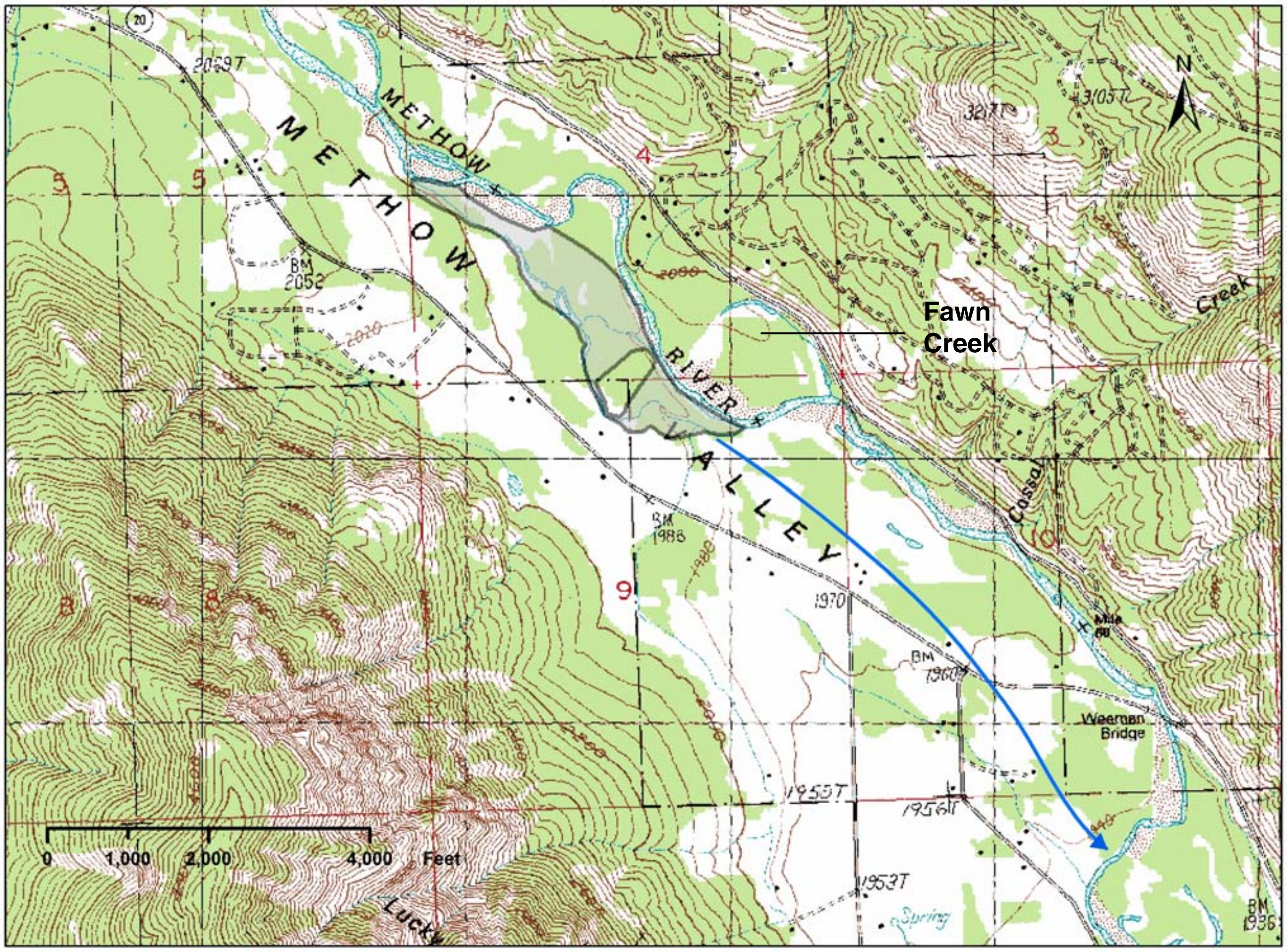


Figure 5. Location of site 2, Methow River at Fawn Creek, in the Methow River Basin, Washington with ground-water flow paths.

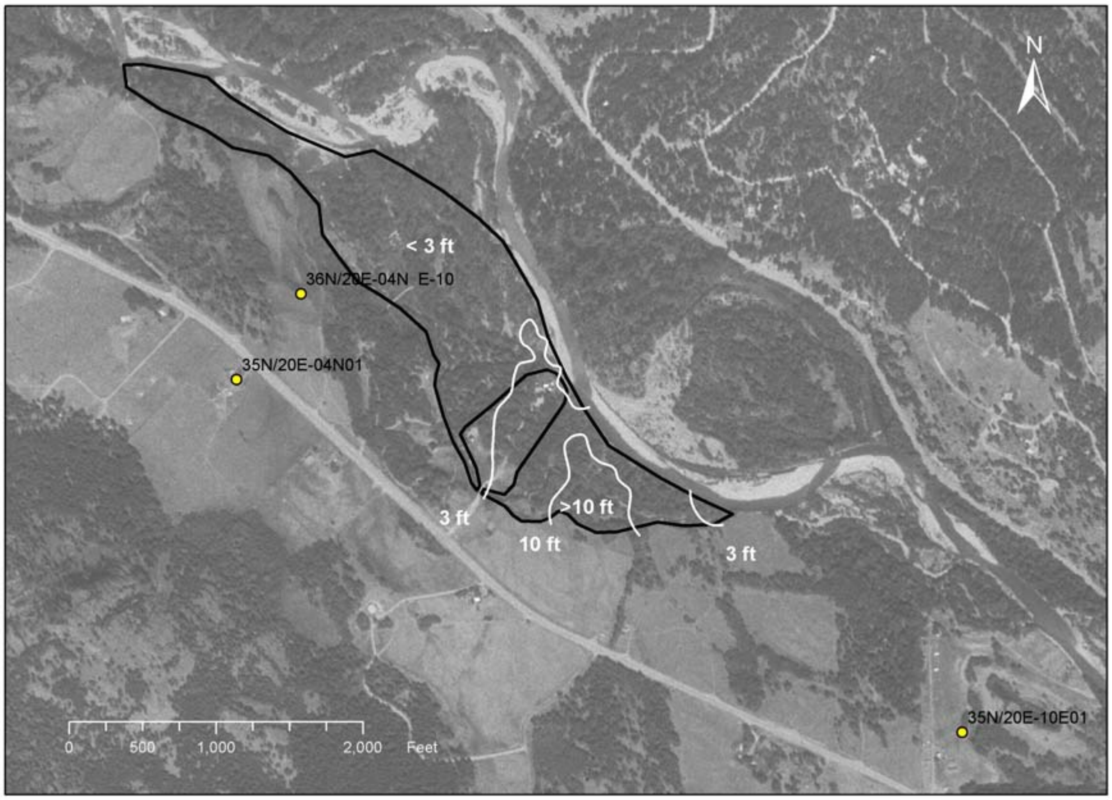


Figure 6. Ground-water wells and estimated depth to ground water at site 2, Methow River at Fawn Creek, in the Methow River Basin, Washington.

Source of digital orthophotograph: U.S. Forest Service, 1998b

3.4. Site 3, Twisp River at War Creek

The floodplain northwest of the Twisp River has a large side channel that begins approximately 500 ft upstream of the confluence with War Creek. It once served as the main channel for the Twisp River (fig. 7). The side channel branches downstream, forming a distributary network that is more than 1,000 ft wide and covers about 50 acres (table 8). The main side channel is 3,300 ft long. The median combined width of the side channels at their banks is 144 ft for three cross sections (table 9).

The unconsolidated sediments are 2,000 ft wide and more than 100 ft thick toward the valley wall. They are likely thicker in the center of the valley under the river. The sediments are mostly coarse sand and gravel. The report for the well at the edge of the study area (33N/20E-07N01) identified the top of “river sand and blue clay” at an altitude of 2,306 ft (depth of 102 ft) and the top of “clay and sandstone” at an altitude of 2,291 ft (depth of 117 ft) (table 10). Because of their depth, these layers are unlikely to affect artificial recharge, however there may be other fine-grained lenses closer to the land surface at the site.

No ground-water levels were available from 2001 for this site, but based on the water surface in the river and the report for well 33N/20E-07N01, depth to the water table is likely to range from 3 to 10 ft below the land surface, although it may be shallower at the upstream and downstream ends of the site (fig. 8). No standing water was observed at the site in April 2003. The unsaturated sediments have a storage capacity of 57 acre-ft (table 8). The primary direction of ground-water flow is likely down valley (fig. 5), in which case horizontal flow paths would be approximately 3,200 ft. The hydraulic gradient between the site and the river is estimated to be 0.01.

Streamflow exceeds regulatory base flow for the Twisp River near Twisp in most years, except during September (fig. 2d). Streamflow generally would not be available for artificial recharge during low-water years at this site.

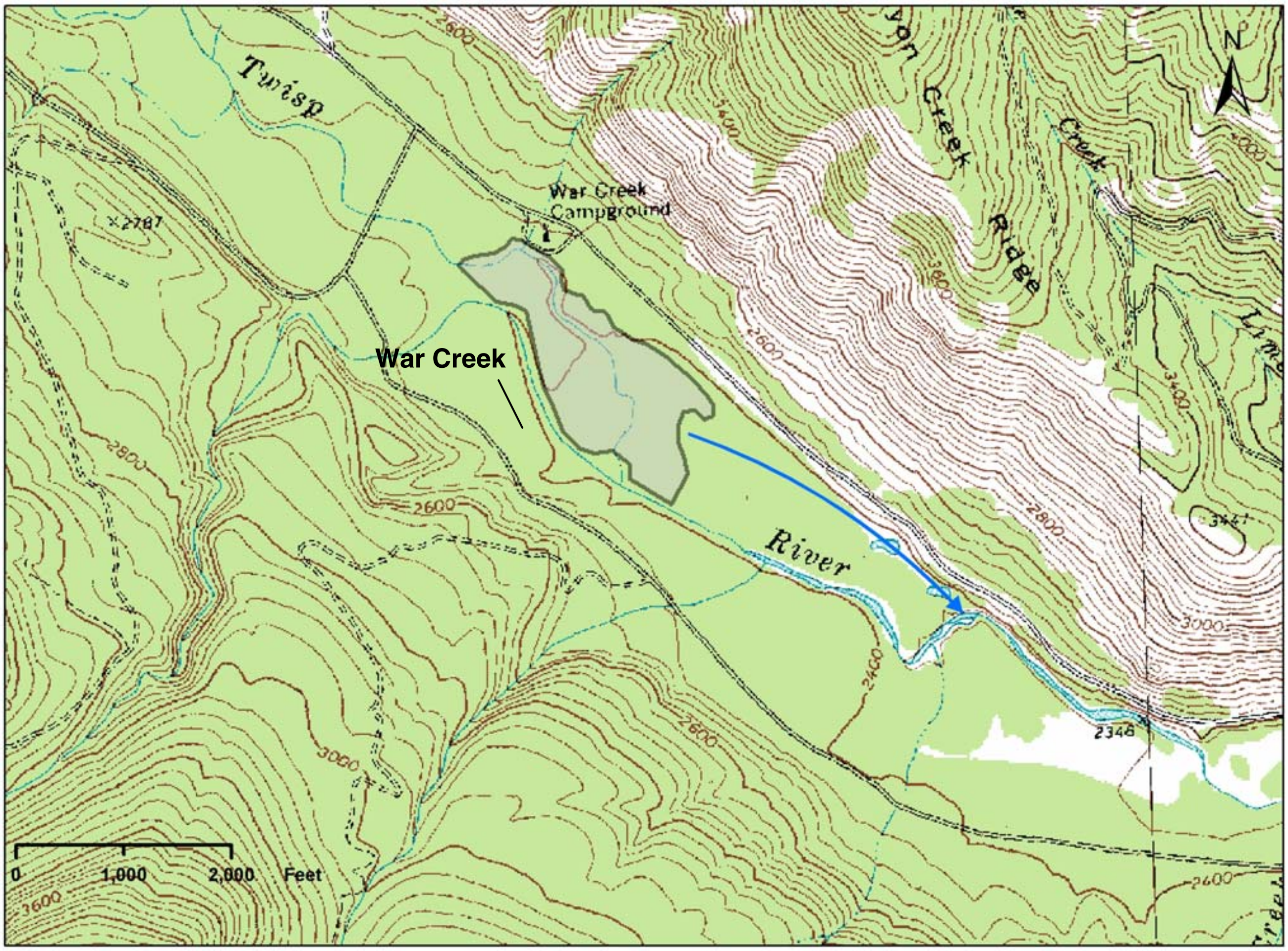


Figure 7. Location of site 3, Twisp River at War Creek, in the Methow River Basin, Washington with ground-water flow paths..

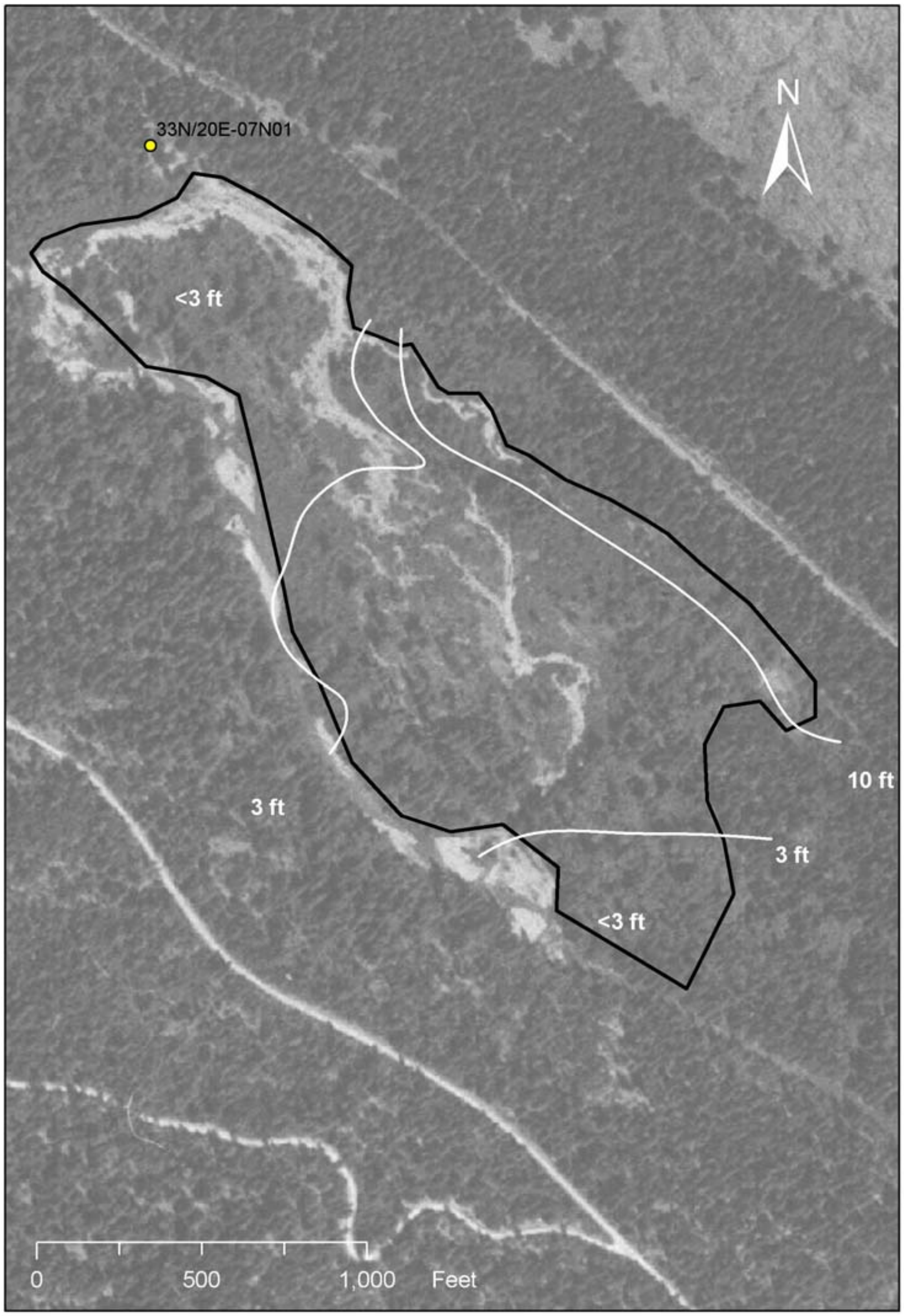


Figure 8. Ground-water well and estimated depth to ground water at site 3, Twisp River at War Creek, in the Methow River Basin, Washington.
Source of digital orthophotograph: U.S. Forest Service, 1998c.

3.5. Site 4, Big Twin Lake

Big Twin Lake is a 78-acre lake formed in a closed depression on a glacio-lacustrine terrace 2 mi south of Winthrop (fig.9). The unconsolidated sediments are more than 100 ft thick in the center of the terrace and are poorly sorted (clay, silt, sand, gravel, cobble, and boulders) and may fill a paleo-channel that is approximately 3,000 ft wide in the bedrock beneath the terrace (Konrad and others, 2003). Potential low-permeability layers were reported in five of six well logs, with tops of the layers reported at an altitude of 1,818 to 1,832 ft in four wells. These layers may not have been continuous, however, as they were reported variously as “clay like” at an altitude of 1,818 ft, “silt” at an altitude of 1,822 ft , “clay” at an altitude of 1,825 ft, and “clay” and “cemented silt” at an altitude of 1,832 ft (table 10). The soil is Owhi extremely stony fine sandy loam with a permeability of 2 to 6 inches per day (Soil Conservation Service, 1980).

The water-surface altitude in the lake is approximately the same as ground-water levels in surrounding shallow wells. Depth to ground water increases to more than 20 ft at a distance of 100 to 1,000 ft from the lake shore as the land surface rises away from the lake (fig. 10). The sediments beneath the lake are saturated, so artificial recharge would rely on storage in the lake, which is equal to 78 acre-ft per foot of rise in the lake level. The saturated thickness of the unconsolidated aquifer is more than 100 ft southeast of the lake (well 34N/21E-15R01). Ground water generally flows to the southeast, with horizontal flow paths to the Methow River that are likely 1.5 to 2 mi long. The hydraulic gradient between the lake and the Methow River along the flow paths ranges from 0.011 to 0.015.

Streamflow for artificial recharge in Big Twin Lake may be available from the Methow River near Winthrop. In this case, the availability of streamflow likely would be limited by regulatory base flow for the Methow River near Pateros. Streamflow also may be available from Wolf Creek, but the period of record for streamflow only began in water year 2001 and Washington State has not established regulatory base flow for Wolf Creek. There is, however, a federal streamflow target established to protect endangered salmonids (National Marine Fisheries Service, 2000), which would likely limit diversions from Wolf Creek for artificial recharge.

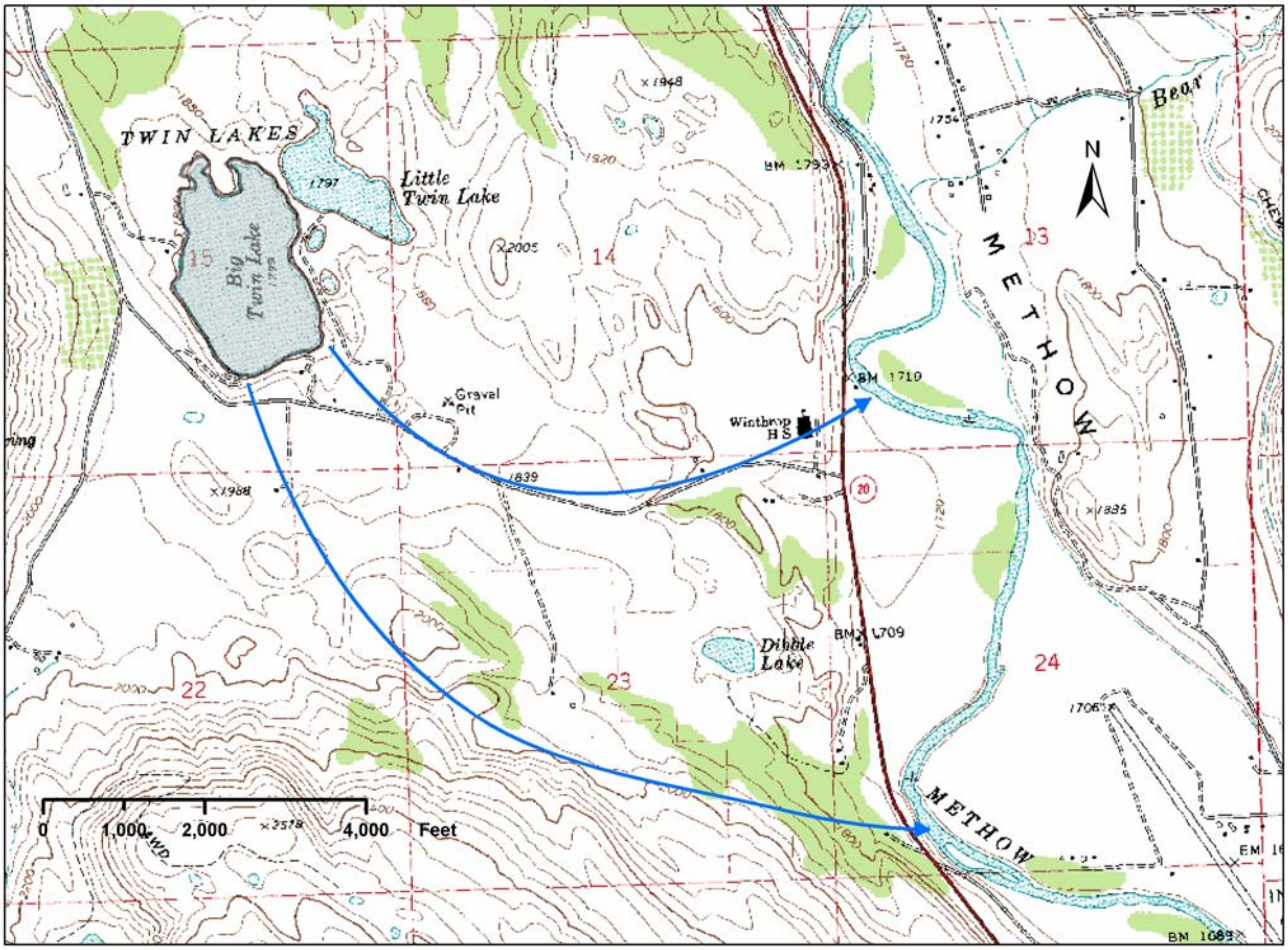


Figure 9. Location of site 4, Big Twin Lake, in the Methow River Basin, Washington with ground-water flow paths.

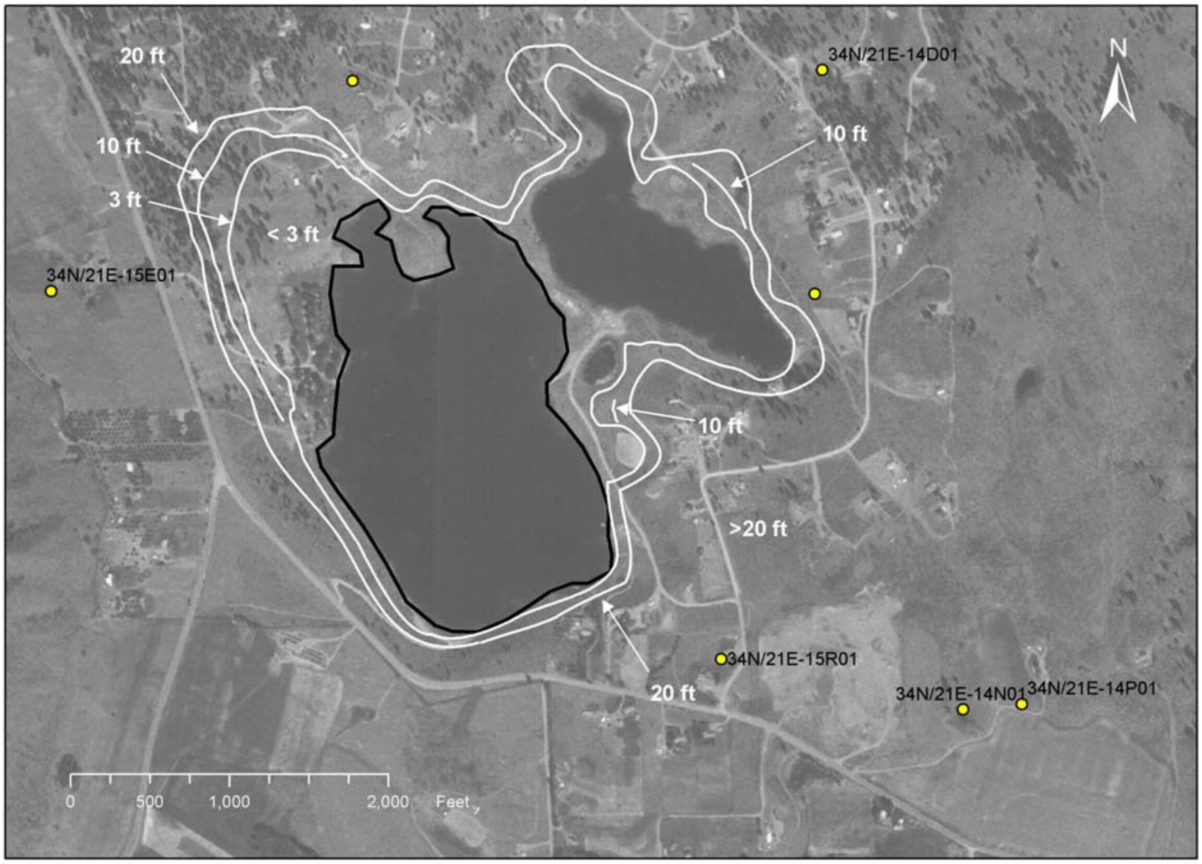


Figure 10. Ground-water wells and estimated depth to ground water at site 4, Big Twin Lake, Winthrop in the Methow River Basin, Washington.
Source of digital orthophotophotograph: U.S. Forest Service, 1998d.

3.6. Site 5, Elbow Coulee

Elbow Coulee is a north-south-trending valley north of the Twisp River (fig. 11). The valley likely was formed through erosion by glacial ice and melt water. The valley is filled with poorly sorted, unconsolidated sediments (clay, silt, sand, gravel, cobbles, and boulders) that are at most 800 ft wide at the land surface, with a total thickness of approximately 50 ft and a saturated thickness of approximately 10 ft at its southern end. The soil in Elbow Coulee is Newbon gravelly loam, with a permeability of 0.6 to 2 inches per day (Soil Conservation Service, 1980).

The depth to the water table is generally greater than 20 ft in the southern part of the site but is likely closer to the land surface in the northern part (fig. 12). The unsaturated sediments have a storage capacity of 2,778 acre-ft (table 8). Ground water flows to the south, down Elbow Coulee toward the Twisp River. Unconsolidated sediments form a terrace along the north side of the Twisp River that is continuous with the sediments filling Elbow Coulee. Ground water seeps from the east side of the base of the terrace to a wetland area adjacent to the river. Ground-water flow paths to the river range from about 1,200 ft at the lower end of Elbow Coulee to about 2.3 mi at the upper end (fig. 11). The hydraulic gradient between the water table in the southern portion of Elbow Coulee and the Twisp River is 0.03.

Surface water from either Wolf Creek or the Twisp River could be used for artificial recharge in Elbow Coulee, although the federal streamflow target established to protect endangered salmonids (National Marine Fisheries Service, 2000) would likely limit diversions from Wolf Creek for artificial recharge. Streamflow exceeds regulatory base flow for the Twisp River near Twisp in most years, except during September (fig. 2d). Streamflow generally would not be available for artificial recharge during low-water years at this site.

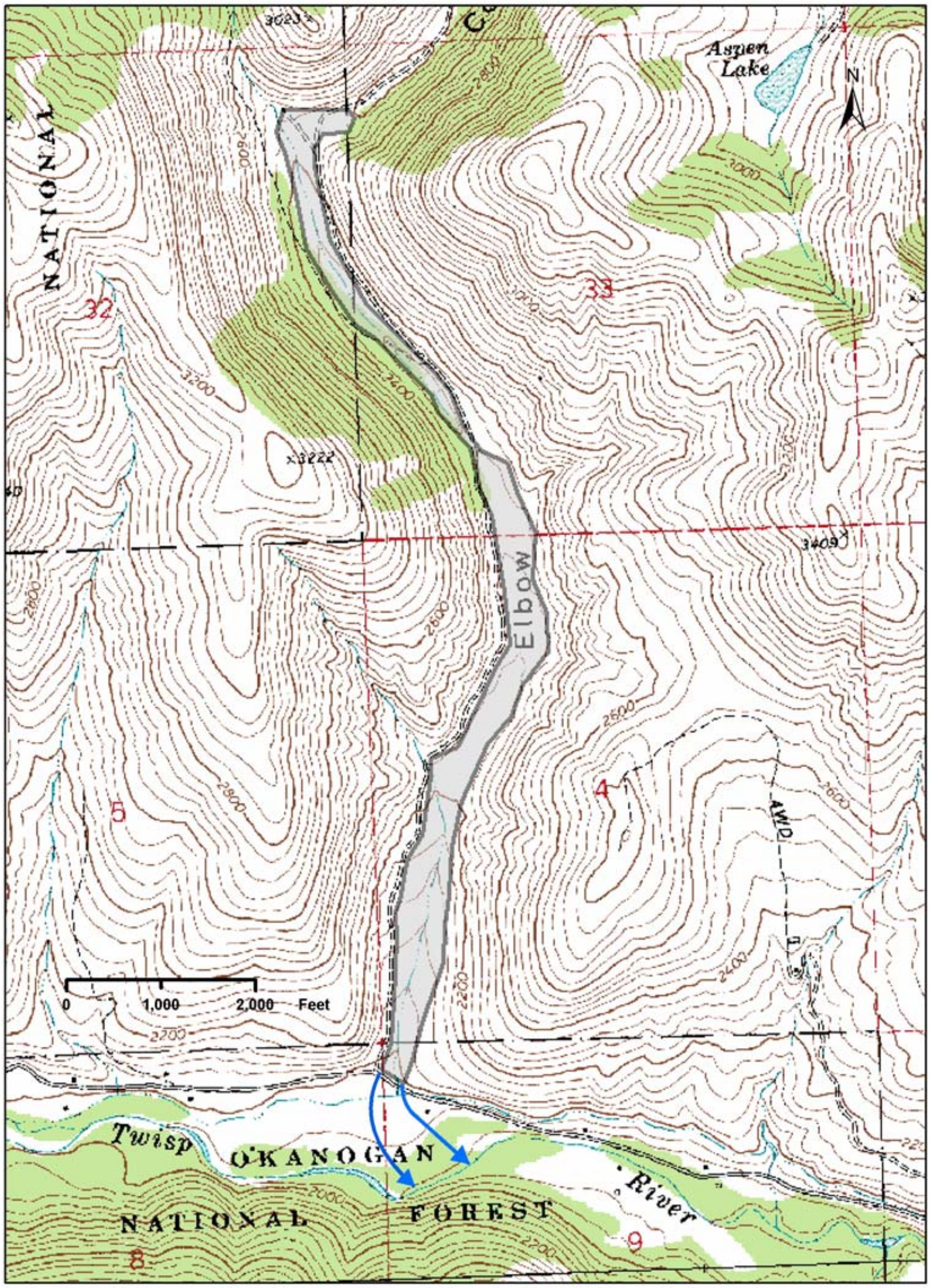


Figure 11. Location of site 5, Elbow Coulee, in the Methow River Basin, Washington with ground-water flow paths.

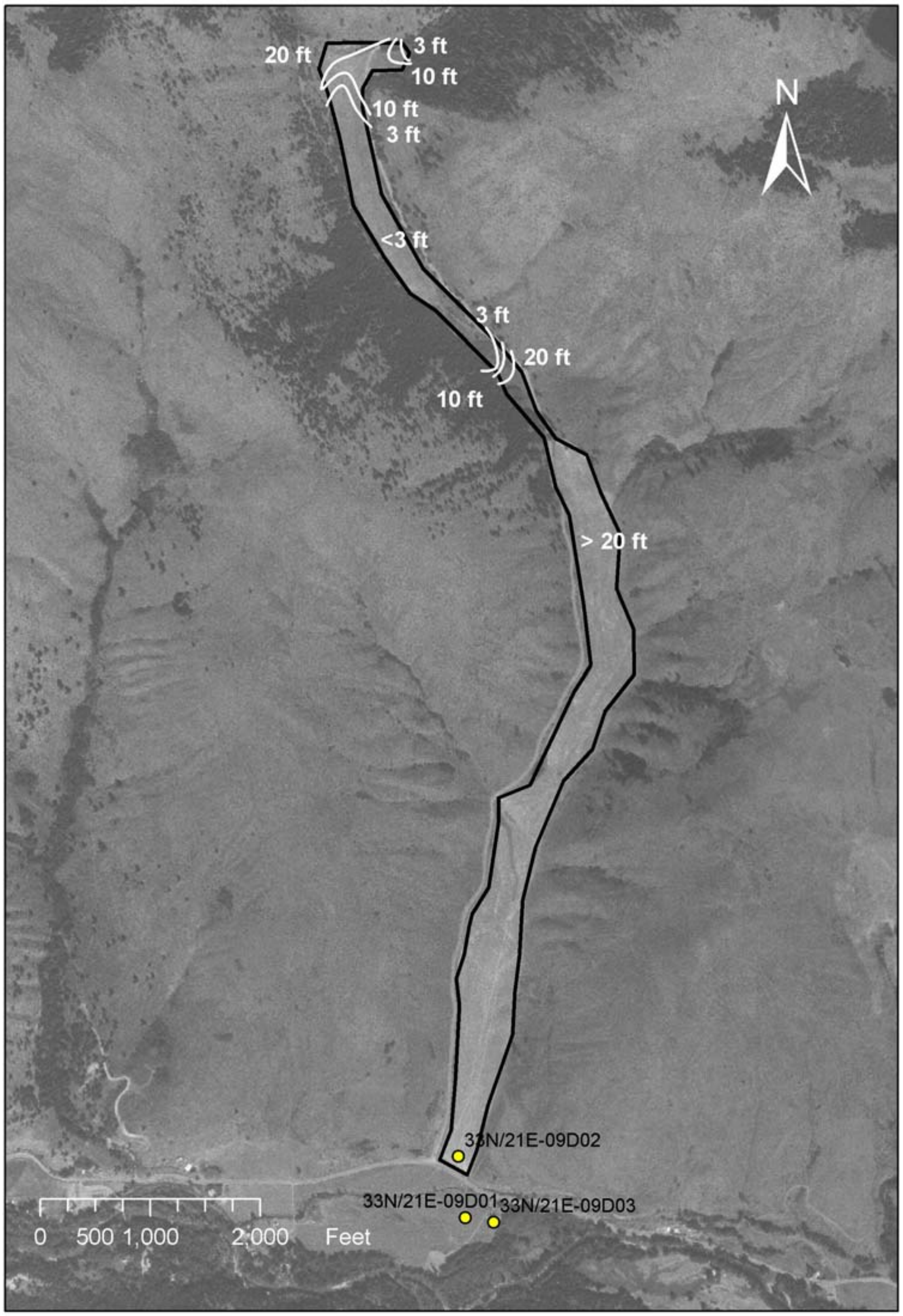


Figure 12. Ground-water wells and estimated depth to ground water at site 5, Elbow Coulee, in the Methow River Basin, Washington.
Source of digital orthophotograph: U.S. Forest Service, 1998d

3.7. Site 6, Terrace Southeast of Twisp

A terrace formed of coarse unconsolidated sediments (sand and gravel) with a thickness of 80 to more than 100 ft is located 1.5 mi southeast of Twisp on the northeast side of the

Methow River (fig. 13). The terrace was deposited over bedrock, which is likely to dip to the southwest toward the Methow River. The soils on the terrace are Newbon gravelly loam, Winthrop gravelly loamy sand, and Newbon loam, which have permeabilities ranging from 0.6 to more than 20 inches per day (Soil Conservation Service, 1980).

The depth to water table is more than 20 ft under the terrace (fig. 14), with two wells (33N/21E-16R [6”] and [8”]) in the terrace having depths to water of 71 and 84 ft. The location of these wells was not confirmed in the field and, consequently, are not shown in fig. 14. The saturated thickness of the unconsolidated aquifer in these wells ranged from 10 to more than 19 ft. The water table under the terrace is higher, by approximately 40 ft, than the ground water in the alluvial deposits along the Methow River to the west. The unsaturated sediments have a storage capacity of 1,066 acre-ft (table 8). Ground-water flow paths from the terrace to the river are about 1,100 to 3,100 ft. (fig. 13). The hydraulic gradient between the water table and the Methow River along the flow paths ranges from 0.007 to 0.02.

Artificial recharge may be feasible at this site only during the spring and summer in years when streamflow is close to average or higher, given the availability of streamflow for the Methow River near Pateros (fig. 2f). The presence of a closed landfill in the vicinity of well 33N/21E-16R03, however, will restrict the area of the terrace that may be used for artificial recharge because of the potential for ground-water contamination.

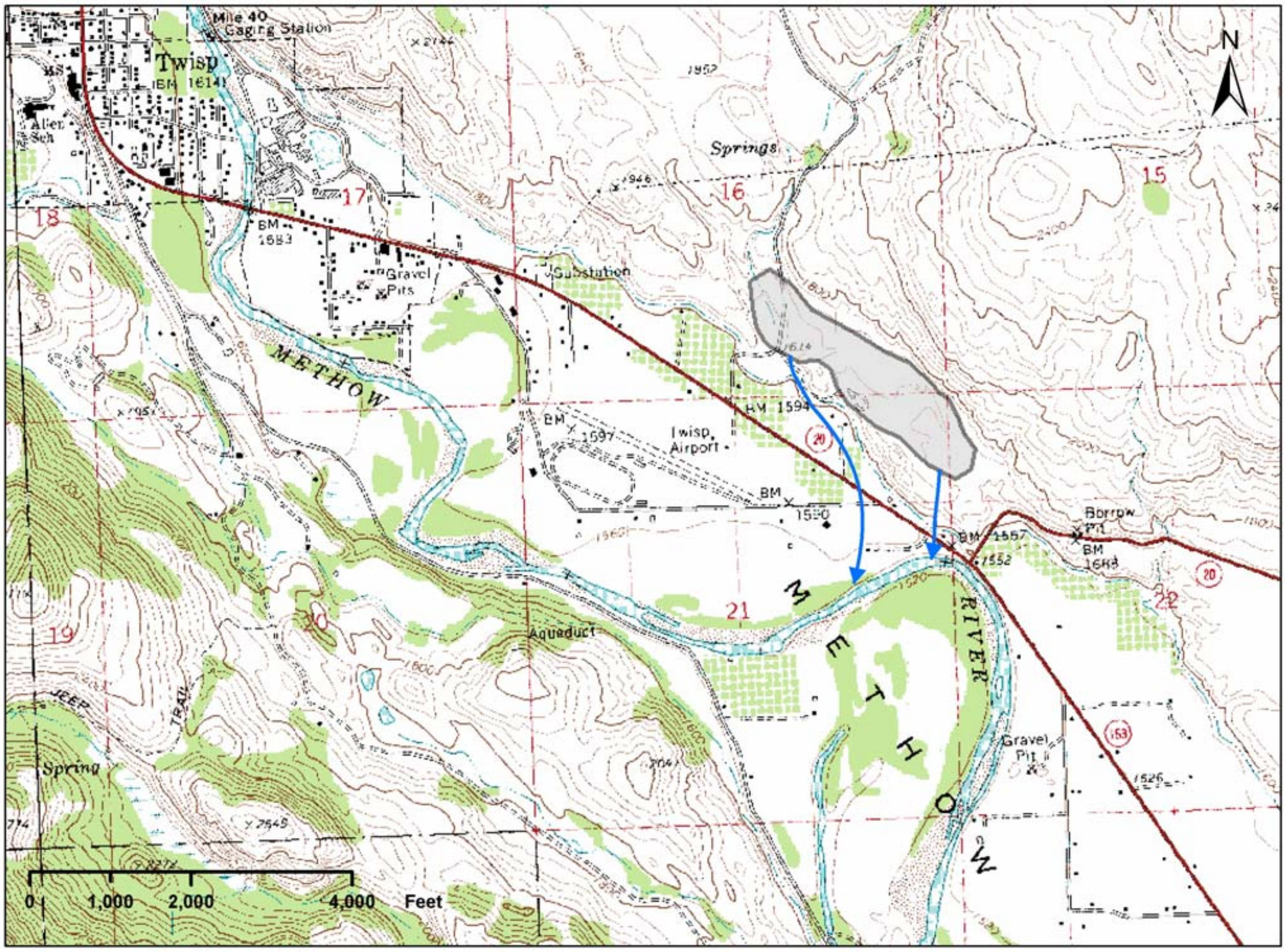


Figure 13. Location of site 6, Terrace south of Twisp, in the Methow River Basin, Washington with ground-water flow paths.

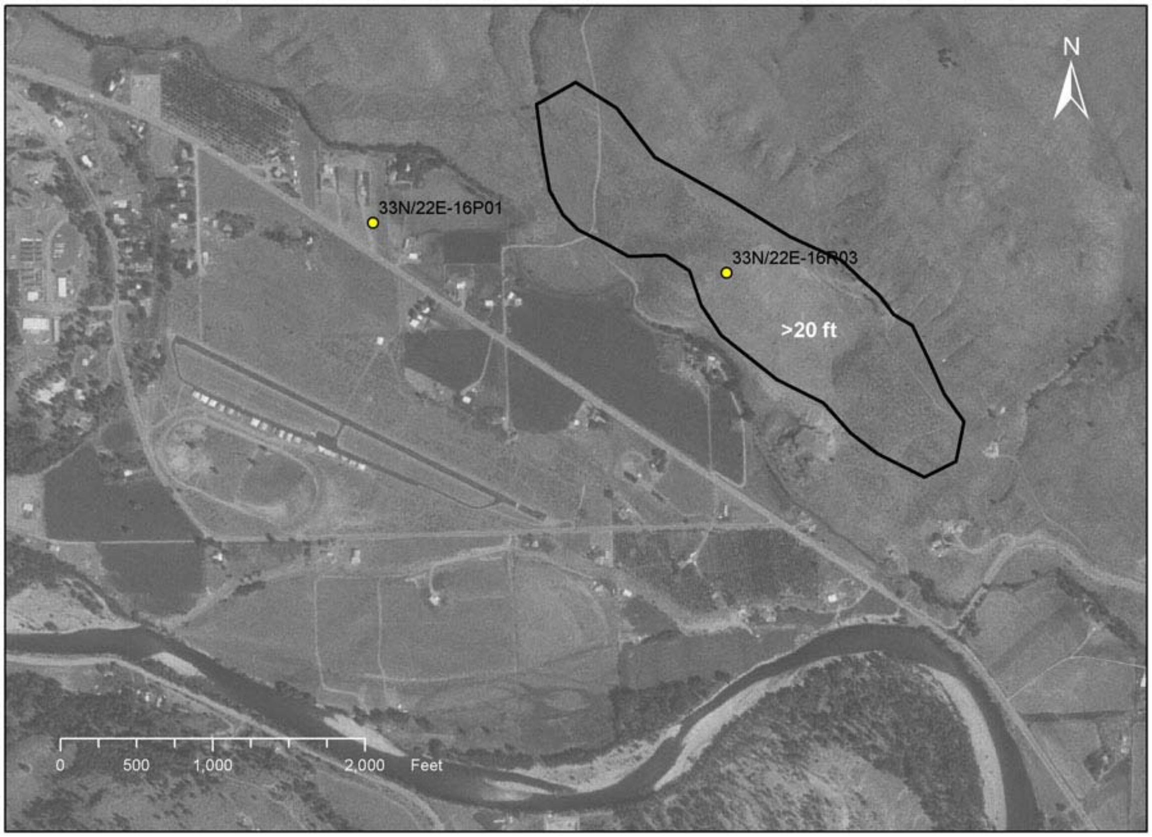


Figure 14. Ground-water wells and estimated depth to ground water at site 6, Terrace southeast of Twisp, in the Methow River Basin, Washington.
Source of digital orthophotograph: U.S. Forest Service, 1998e.

4. Potential Hazards Associated with Artificial Recharge

Artificial recharge increases ground-water levels and flow rates, which may pose hazards including flooding, hill-slope instability, mobilization of contaminants, and environmental changes. Potential hazards of artificial recharge were not assessed comprehensively at any of the sites. In general, increased ground-water levels will increase flooding associated with ground-water seepage and hill-slope instability. Increased ground-water levels also can mobilize and transport contaminants from previously unsaturated soils to the water table. Contaminant mobilization is particularly a potential hazard at site 6, where solid wastes were buried in a closed landfill, and site 4, where drainfields for septic systems may be close to the water table. Contaminants on the land surface also may be transported by water infiltrating into soils, including areas where hazardous material were stored or airborne contaminants were deposited on the land surface. Artificial recharge likely would change environmental conditions at and around a site that could include marshy conditions, saturated soils, and increased stage in wetlands. Artificial recharge is also likely to increase evaporation and transpiration. Over the long term, increased evaporation could increase soil salinity.

5. Assessment of Hydrogeologic Conditions at Artificial-Recharge Sites

The hydrogeology of unconsolidated sediments in the Methow River basin varies spatially with regard to a number of important conditions that could affect aquifer recharge, including depth to the water table, hydraulic gradient, and length of flow paths to a river. The water table at the Methow River above Early Winters and the Twisp River at War Creek are likely deep enough to allow artificial recharge throughout the year, except for periods of sustained high streamflow in some years. Ground water at the Methow River at Fawn Creek is shallow, so there is little storage capacity available in the aquifer at the site and water that is recharged is likely to flow along shallow, horizontal paths quickly back to the river. The water tables at Big Twin Lake, Elbow Coulee, and the terrace south of Twisp are likely deep enough to allow artificial recharge throughout the year and, in particular, during periods of high flows when streamflow generally would be available for artificial recharge.

Because of the deep water table and saturated thickness of the aquifer at Methow River above Early Winters Creek, the Twisp River at War Creek, and Big Twin Lake, ground-water flow is less likely to be affected by artificial recharge at these sites than at the other sites. In contrast, artificial recharge at the Methow River at Fawn Creek, Elbow Coulee, and the terrace south of Twisp likely would cause changes in the direction and velocity of ground-water flow.

Artificial recharge also is likely to cause local mounding of the water table and, as a consequence, increased ground-water flow from the recharge site. Mounding will reduce the storage capacity of the aquifer as the water table approaches the land surface and will reduce the residence time of recharged water. In general, ground-water mounding will be minimal where the aquifer is wide and has a large saturated thickness, a high hydraulic gradient, and high hydraulic conductivity. Based on these conditions, the floodplain sites and Big Twin Lake are likely to have least mounding in response to aquifer recharge. Any mounding at the floodplain sites, however, could result in shallow, horizontal ground-water flow back to the river, particularly for the Methow River at Fawn Creek, where the water table is naturally shallow.

The same hydrogeologic conditions that reduce mounding, however, also limit the effect of artificial recharge at these sites on increased ground-water discharge to streams. In contrast, artificial recharge at Elbow Coulee and the terrace south of Twisp might produce the largest seasonal (temporary) increase in streamflow of any of the sites after periods of artificial recharge because of mounding that would increase the already high hydraulic gradients between these sites and the respective rivers. The potential ground-water flow paths from Elbow Coulee back to the Twisp River are longer than the flow paths from the terrace south of Twisp back to the Methow River. The longer flow paths could provide a longer delay between periods of artificial recharge and inflow back to the river, assuming similar hydraulic conductivity and gradients at the two sites. Flow paths at Big Twin Lake also are long, and that would delay the return of artificially recharged water to the Methow River.

Overall, two sites have conditions that are not suitable for artificial recharge. The terrace south of Twisp has a closed landfill, which represents a potential source of contaminants that artificial recharge could mobilize and transport. The Methow River at Fawn Creek has a high water table that would make artificial recharge infeasible. Artificial recharge at the other sites likely is feasible, but would depend on the specific objectives of a recharge project.

6. Summary

Artificial recharge is a means for re-distributing water resources in the Methow River Basin from periods of high runoff, during the late spring and early summer, to periods of low runoff later in the year. An analysis of streamflow records for water years 1993-2002 indicates that annual streamflow volumes exceed the volume required to meet Washington State regulatory base flows in all but drought years (such as water year 2001) at the six gages where regulatory base flows have been established in the MRB. Excess streamflow is available in most years during late spring and summer for all gages: streamflow exceeded regulatory base flow from May through August at all gages for 7 out 10 years in the period from water years 1993-2002. Streamflow was less than regulatory base flow from September through March at some gages, including the Methow River near Pateros. Because any artificial recharge would occur upstream of Pateros, new surface-water diversion for artificial recharge may not be possible from September through March in most years.

Artificial recharge on floodplains may be feasible where the water table is relatively deep during periods when streamflow is available (for example, the Methow River above Early Winters Creek and the Twisp River at War Creek). Lenses of fine-grained sediments, however, could impede vertical ground-water flow, in which case the sediments under a recharge site would become saturated and recharged water would flow laterally back into the rivers. Artificial recharge likely is feasible on terraces and valley fill deposits, but hazards including contaminant transport, seepage of ground water to the land surface, and hillslope instability must be considered. The relatively long ground-water flow paths between the Elbow Coulee and Big Twin Lake are likely to provide longer residence times for artificially recharged water than at other sites.

7. References

Konrad, C.P., Drost, B.W., and Wagner, R.J., 2003, Hydrogeology of the unconsolidated deposits, water quality, and ground-water/surface-water exchanges in the Methow River Basin, Okanogan County, Washington: U.S. Geological Survey Water-Resources Investigations Report 03-4244, 137 p.

National Marine Fisheries Service, 2000, Biological Opinion for the Wolf Creek Irrigation Ditch, Okanogan National Forest: National Marine Fisheries Service Northwest Region, Seattle, Washington, 38 p.

Soil Conservation Service, 1980, Soil survey of Okanogan County: U.S. Department of Agriculture, 153 p. + 105 sheets.

U.S. Forest Service, 1998a, Digital orthophoto of the Mazama quadrangle, image taken on July 8, 1998, accessed on October 17, 2002, at http://rocky.ess.washington.edu/data/raster/usfs/concrete/images/48120e4_1998.zip.

U.S. Forest Service, 1998b, Digital orthophoto of the Rendevous quadrangle, image taken on July 8, 1998, accessed on October 17, 2002, at http://rocky.ess.washington.edu/data/raster/usfs/concrete/images/48120e3_1998.zip.

U.S. Forest Service, 1998c, Digital orthophoto of the Oval Peak quadrangle, image taken on July 8, 1998, accessed on October 17, 2002, at http://rocky.ess.washington.edu/data/raster/usfs/concrete/images/48120d2_1998.zip.

U.S. Forest Service, 1998d, Digital orthophoto of the Winthrop quadrangle, image taken on July 8, 1998, accessed on October 17, 2002, at http://rocky.ess.washington.edu/data/raster/usfs/concrete/images/48120c1_1998.zip.

U.S. Forest Service, 1998e, Digital orthophoto of the Twisp East quadrangle, image taken on July 8, 1998, accessed on October 17, 2002, at http://rocky.ess.washington.edu/data/raster/usfs/concrete/images/48120c4_1998.zip.

U.S. Geological Survey, 2003, The National Map Seamless Data Distribution System Viewer, accessed on October 20, 2003 at http://seamless.usgs.gov/viewer.htm.

Washington Department of Ecology, 2003, Water well log reports, accessed on October 20, 2003 at http://apps.ecy.wa.gov/welllog/.